CHAPTER 7. Risk modelling: land vulnerability expert system

D. de la Rosa, J.W.H.C. Crompvoets and F. Mayol
Consejo Superior de Investigaciones Científicas, Instituto de Recursos Naturales y Agrobiología, Apdo 1052, E-41080 Sevilla, España.

7.1. Introduction

The land vulnerability models were constructed partly in accordance with the criteria of the FAO-framework for Land Evaluation. They were developed using the ALES shell (Rossiter, 1990), which is a computer program that allows land evaluators to build expert systems. The expert systems created are based on decision trees, which are hierarchical multiway keys in which the leaves are results such as land quality ratings, and the interior nodes of the tree are decision criteria such as land characteristic values. Decision trees appear very valuable as tools to predict the impact of agricultural activities and global changes on land suitability, vulnerability and sustainability. Further, land evaluation, according to the criteria of the FAO framework, is more accessible and transparent to the user, when decision trees are used rather than the usual matching-tables. In addition to this, some land qualities cannot necessarily be characterised by simulation modelling (Bouma *et al.*, 1993a, b). The decision trees created by this project are formed by using expert knowledge (experience), specialists, land users, and collected literature. It seemed a reasonably accurate way of classifying soil vulnerability (erosion and soil/groundwater contamination) of a particular land unit.

7.1.1 Background

The land evaluation activities of this group are derived from the work of De la Rosa *et al.* (1992, 1993). The bio-physical land use evaluation and environmental impact evaluation of land management (named MicroLEIS) appeared to be an ideal framework within which to develop an agro-ecological approach. This PC -based land evaluation information system was developed for optimal allocation of agricultural and forestry land use systems under Mediterranean conditions. The outline of the methodology, which is in general accordance with the FAO Framework for Land Evaluation (FAO, 1976), with new criteria for evaluating sustainable land management, integrates several land capability, soil suitability, yield prediction and field vulnerability models. The system uses basic input data or “key” parameters from soil research and other natural resource inventory information, which are readily available. Further, it applies automated qualitative procedures, statistical models and expert system techniques. MicroLEIS was designed and constructed to be applied as a sequential and user-friendly set of tools. Input data are entered from the computer keyboard for each soil, land or field unit to be evaluated, following a menu system and explanation screens. Figure 7.1 outlines the interactions of the different types of data with the land evaluation frameworks using different kinds of databases. The interfaces between the databases and the land evaluation framework are through land suitability and vulnerability models. By combination of these two types of models it is possible to define sustainable land use and management.

7.1.2 Terminology and concepts

Evaluating-scenario (ES). Complete set of observation sites or evaluating units which can be classified and reclassified by the different evaluation models.

Evaluating-unit (EU). General term to identify the spatial unit of analysis or observation site to be evaluated by the soil erosion and contamination models.

Field-unit (FU). EU which is considered to be the natural and technical environment within which agricultural production takes place. A FU is characterised by LCs and MCs. This is the EU for the soil erosion and contamination models.

Land-unit (LU*). EU which is the focal point in land evaluation. A LU is considered to be spatially homogeneous in terms of all elements of the physical environment: climate, site, soil and use. This is the EU for the soil erosion and contamination models.

Soil-unit (SU). EU which is considered to be the basic building block for developing soil interpretations. Soil series, the lowest category of any hierarchical taxonomic classification, is the most homogeneous and closely related to the central concept of a SU. This is the EU for the soil and contamination models.

Field Utilisation Type (FUT). This is an extension of the LUT, with special attention to agronomic or management characteristics (crop properties and cultivation practices), exclusively described in technical terms.

Land Characteristic (LC*). Attribute of land that can be measured or estimated, and which can be employed as a mean of describing LQs or distinguishing between LUs of different suitabilities or vulnerabilities for use. It considers basically of climate, site and soil factors.

Land Quality (LQ*). Complex attribute of land which acts in a manner distinct from the actions of other LQs in its influence on the suitability of land for a specific kind of use.

Land Use Requirement (LUR*). Each LUT poses specific requirements to the land.

Land Use System (LUS). This is a combination of one LU and one LUT. Without socio-economic considerations, a LUS is equivalent to a FU.

Land Utilisation Type (LUT*). This is a more specific interpretation of land use which considers the biophysical, technical and socio-economic attributes of a LU.

Management Characteristic (MC). Attribute of management that can be estimated and which can be employed as a mean of describing MQs. It considers basically crop properties and cultivation practices.

Management Quality (MQ). Complex attribute of management which acts in a manner distinct from the actions of other MQs in its influence on the suitability or vulnerability of a field for specific kind of use.

(*) Traditional terms defined in the land evaluation FAO Framework (1976)

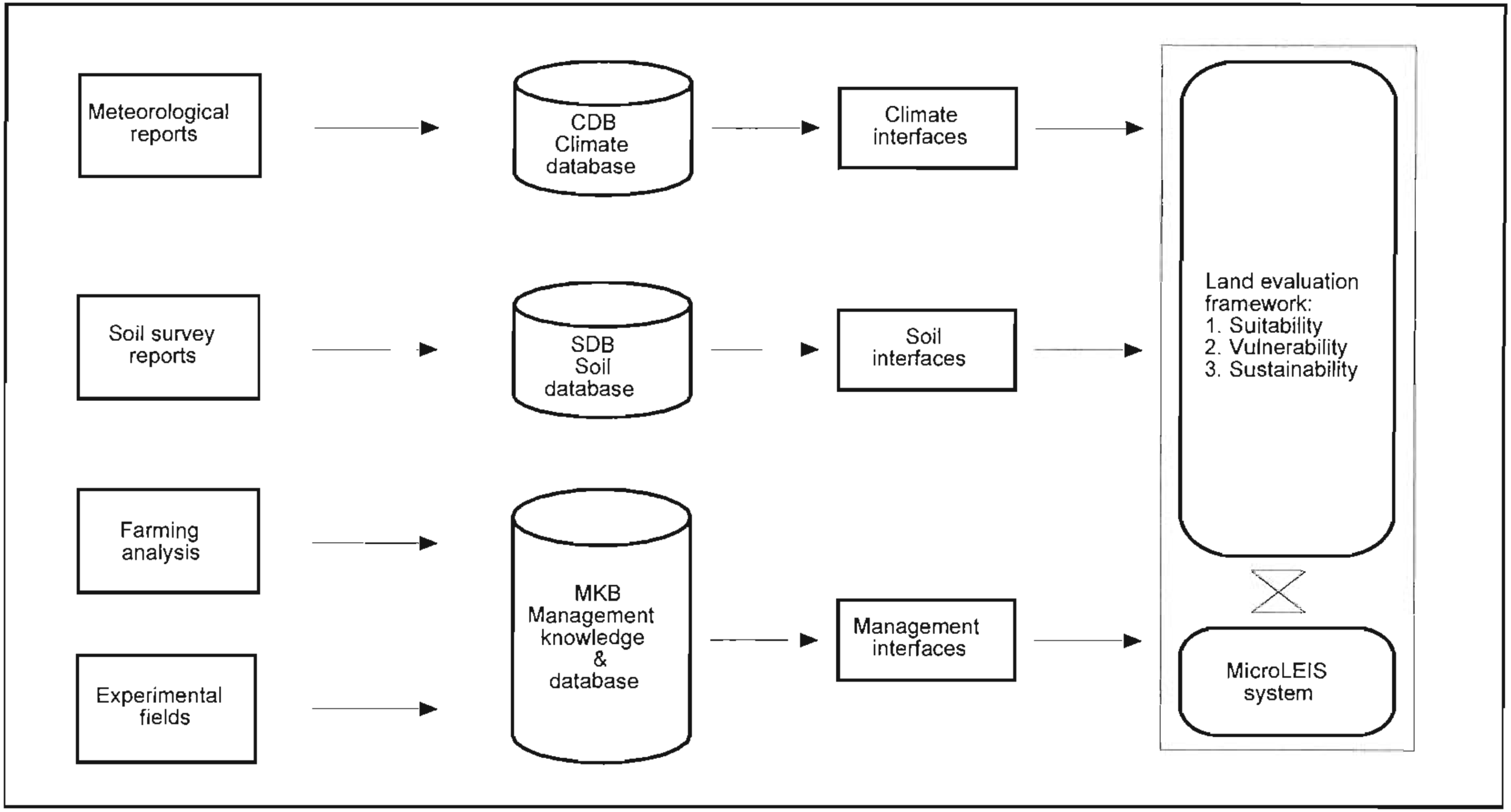

Figure 7.1 Global diagram of MicroLEIS land evaluation system.

The **attainable vulnerability** (AR) refers to the land vulnerability of a land unit to degradation type, in one or more of its ecological functions, within the constraints of its bio-physical characteristics, without considering vegetation or crop and management factors. The model separates the attainable vulnerability classes for each vulnerability type. The spatial unit of evaluation is the land unit.

The **management vulnerability** (MR) considers the risk of a particular Field Utilisation Type to a degradation type. It is independent of environmental or socio-economical constraints. The model separates the management vulnerability classes for each vulnerability type. The unit of evaluation is the Field Utilisation Type (FUT).

The **Actual vulnerability** (AC) considers simultaneously the biophysical and management risk factors of a particular field unit. The model separates the actual vulnerability classes for each vulnerability type. The spatial unit of evaluation is the field unit.

The combination of the all the attainable vulnerability classes forms the attainable total index (ARi). Also, the combination of all the management vulnerability classes forms the management total index (MRi). Finally, the combination of attainable and management indices forms the actual total index (ACi).

7.1.3 Knowledge and data capture

a) Basic data

The data are derived from meteorological reports, soil survey reports, farming analyses and experimental fields. For Andalucia, 62 weather stations with monthly max. and min. temperature and precipitation have been collected. Five of the stations contain daily data and, additionally, contain data of potential evaporation, insolation, relative humidity, and wind direction and speed. For the European meteorological data, "Climate data for the planet Earth. Version 2.0" (Weather Disc Associates, 1990) has been used.

The soil data were collected for Andalucia Occidental (in total around 980 agricultural and non-agricultural soil profile descriptions). In general, the soil profile descriptions show morphological, chemical and physical data. The different evaluation models were based on information from the 62 benchmark soils of Andalucia (De la Rosa, 1984), and the 42 benchmark soils of the European Community (Commission of the European Communities, 1986).

A dataset/inventory of agricultural management was created for the most representative annual and perennial crops in Andalucia from literature sources and interviews with farmers, experts, specialists and extension personnel. The annual crops are wheat, sunflower, barley, cotton, sugar beet, maize, tobacco, rice and potato. The semi- perennial crops are alfalfa, olive/table, olive/oil, vine/table, vine/wine, citrus/bitter, citrus/sweet and almond.

Experimental fields were used to collect data to evaluate and to validate EuroACCESS-II under Andalucian conditions. One experiment on modelling of sunflower growth was a two year 3x3 experiment (1993, 1994) with 3 different sunflower varieties (Florasol, Islero and Isostar), 3 different treatments (full irrigation, restricted irrigation and no irrigation) and 3 replicates. The field was located at the experimental farm of the CSIC-IRNAS "La Hampa" near Coria del Rio (15 km south of Sevilla), and was divided in 28 plots of 20*5.6 m. Each plot consisted of 8 rows. The plant density varied from 50,000 to 90,000 plants ha^{-1}. Every three weeks the plant partitioning, leaf area, stem length/diameter and root length were measured for 5 randomly chosen plants for each plot. The soil moisture content was measured every week. The soil experiments were carried out in the second year (Barros, 1996).

Besides the experiment at Coria (Vega Alluvial, Xerofluvent, calcaric Fluvisol) two other sites have been applied to validate EuroACCESS-II:

- Utrera (Tierra Negra Andaluza, Pelloxererts, calcaric Vertisol);
- Jerez de la Frontera (Rendzina, Xerothents, calcaric Regosol);

The soil classifications according to the local system, Soil Taxonomy (USDA, 1975) and FAO (1988) are given in brackets. According to the input questionnaire given by the Montpellier group, it was impossible to find more sites to validate EuroACCESS-II within the test area, because detailed soil and crop data are very scarce in this region. The soil data were derived from the PhD thesis of Arrue Ugarte (1976). The crop and management data were derived from annual reports of RAEA (Red Andaluza de Experimentacion Agraria) with reference to sunflower and winter wheat. The daily climate data are captured from meteorological stations of the Instituto Nacional de Meteorologia, which are situated at a distance of 0 to 10 km from each site. In summary, the sites with their related crop(s) and year(s) are:

- Coria de Rio: sunflower (1993)
- Utrera: wheat (90/91)(91/92), sunflower (91/92)
- Jerez de la Frontera: wheat (90/91) (91/92), sunflower (90/91) (91/92)

b) Knowledge

Useful knowledge about soil erosion and contamination processes was captured mainly by interviews and discussions with a with range of land users, experts and specialists, each with a specific focus. According to FAO (1983), a strong attempt was made to obtain fresh answers by avoiding the supply of standardised forms listing land qualities and their classes. The expert team was composed of 48 specialists, selected from planning-oriented agencies and academic faculties from The Netherlands (Agricultural University; Staring Centre; ISRIC; Wageningen; Oranjewoud; Rotterdam), New Zealand (Horticulture and Food Research Institute), Germany, United Kingdom (SSLRC, Silsoe and ADAS, Cambridge), Poland (IAP-PAN), Hungary (RISSAC; VITUKI, Budapest), Romania (RISSA; NIHMB, Bucharest), France (INRA, Montpellier; LTHE-IMG, Grenoble), Italy (FAO, Rome) and Spain (CSIC, Algeria and Sevilla; CIDA, Cordoba; RAEA, Junta de Andalucia, Agencia de Medio Ambiente, Sevilla). In addition, 32 land users came from The Netherlands and Spain. The contacts were written and oral (Crompvoets *et al.*, 1994). All of the experts were asked the following questions:

1. select and define the main types of soil erosion and (agro)chemical compounds which contaminate ground and surface water in Europe, rank them into order of importance

and define the number of vulnerability classes of each type.
2. list the land and management qualities that would be important in determining the field vulnerability to soil erosion or to a particular (agro)chemical compound and estimate the ranges of values for each land quality class.
3. define land and management characteristics to be used to define the various land and management quality and define the number of classes to be distinguished and its ranges.

An important comment on the questions was that the number of land characteristics had to be minimised and their data had to be easily available. The land users were sent a questionnaire to describe their Field Utilisation Type (FUT). Afterwards, the results were discussed with specialists of a particular contamination focus, and the decision trees were built with their help. In addition to personal contacts, scientific and company product literature was an important source of data for construction of the model, especially Batjes and Bridges (1991, 1993), Barth and L'Hermite (1987) and Morgan (1979).

7.2 Soil erosion vulnerability expert model

Vulnerability is the capacity of the soil system to be harmed in one or more of its ecological functions, such as production of biomass, filtering, storage, buffering and transportation of substances. The system created assesses qualitatively the vulnerability of European soils to water and wind erosion, especially for agricultural land. The model, developed using expert system techniques, predicts three different types of soil erosion vulnerability: attainable, management and actual. The attainable soil erosion vulnerability is dependent on relief, soil erodibility and rainfall erosivity (stable and physical factors), as Land Qualities. The attainable wind erosion vulnerability is only dependent on wind erodibility. The management vulnerability is dependent on recent land use and land management (technical factors). Management qualities (MQs), crop properties and cultivation practices, represent these management factors. Actual erosion vulnerability is the combination between attainable and management vulnerability (Crompvoets *et al.*, 1993). Figure 7.2 shows the general scheme of the relationships between LQs and MQs, attainable, management and actual erosion vulnerability (see Section 7.4). Only the attainable submodel is included in the EuroACCESS I model, because the management part is based on the local level, and has been checked only in Andalucia. A characteristic of qualitative methods is the use of expert knowledge derived from the experiences of, for example, farmers and soil surveyors. The Automated Land Evaluation System, ALES (Rossiter *et al.*, 1988; Rossiter, 1990; Rossiter and Van Wambeke, 1992) was used to capture the expert knowledge in a computer system. The ALES system is a framework for evaluators to build their own expert model in accordance with FAO's Framework for Land Evaluation (FAO, 1976). With ALES, decision trees can be defined to represent the expert knowledge. These trees are structured representations of a reasoning process needed to combine basic data and expert knowledge to reach decisions (Van Lanen, 1991). ALES was used to estimate the field vulnerability in six steps:

1. Formulations of field vulnerability to soil erosion or (agro)chemical soil, surface and groundwater contamination by different attainable and management types.
2. Selection and definition of relevant land and management qualities, which have an important influence on the attainable and management type being considered.
3. Selection of relevant land and management characteristics, which influence the selected land and management qualities.
4. Creation of decision trees of the land and management qualities by combination of land or management characteristics. Definition of the severity levels and size classification for each land and management characteristic.
5. Creation of decision trees of the attainable and management vulnerability types by combination of land and management qualities. Definition of vulnerability classes.
6. Combination of attainable and/or management vulnerability types by using decision trees to infer the relative attainable, management vulnerability and the actual vulnerability types for each field unit. The field units are allocated to vulnerability classes.

In our study, the knowledge-base system of ALES was used to compute the physical vulnerability. We did not have to take advantage of ALES' ability to perform economic land evaluation. In the recent versions of ALES there are no options for management characteristics and qualities, so it is impossible to evaluate actual vulnerability easily. Another disadvantage of using ALES is that it is not designed to evaluate field vulnerability issues, only land suitability. Initially almost all the decision trees were developed within the ALES-framework, because it was an easy and fast way to validate and calibrate the decision trees (an example is shown in Table 7.1). Afterwards the whole system was translated into MICROSOFT-C++™ and FORTRAN™.

7.2.1 The assessment approach

a) Water erosion

This is a two phase process consisting of the detachment of individual particles from the soil mass and their transport by water. When sufficient energy is no longer available to transport the particles, a third phase, deposition, occurs (Morgan, 1979). The classification of the attainable water erosion vulnerability (AR1) is based on three LQs: LQ1 Relief, LQ2 Soil erodibility and LQ3 Rainfall erosivity.

LQ1 Relief represents the erosion which would normally be expected to increase with increased slope steepness and slope length as a result of increases in velocity and volume of surface run-off. Further, whilst on a flat surface raindrops splash soil particles randomly in all directions, on sloping ground more soil is splashed downslope than upslope, the proportion increasing as the slope steepens. LQ1 is formed by a combination of two LCs: Landform (physiographical position) and Slope gradient.

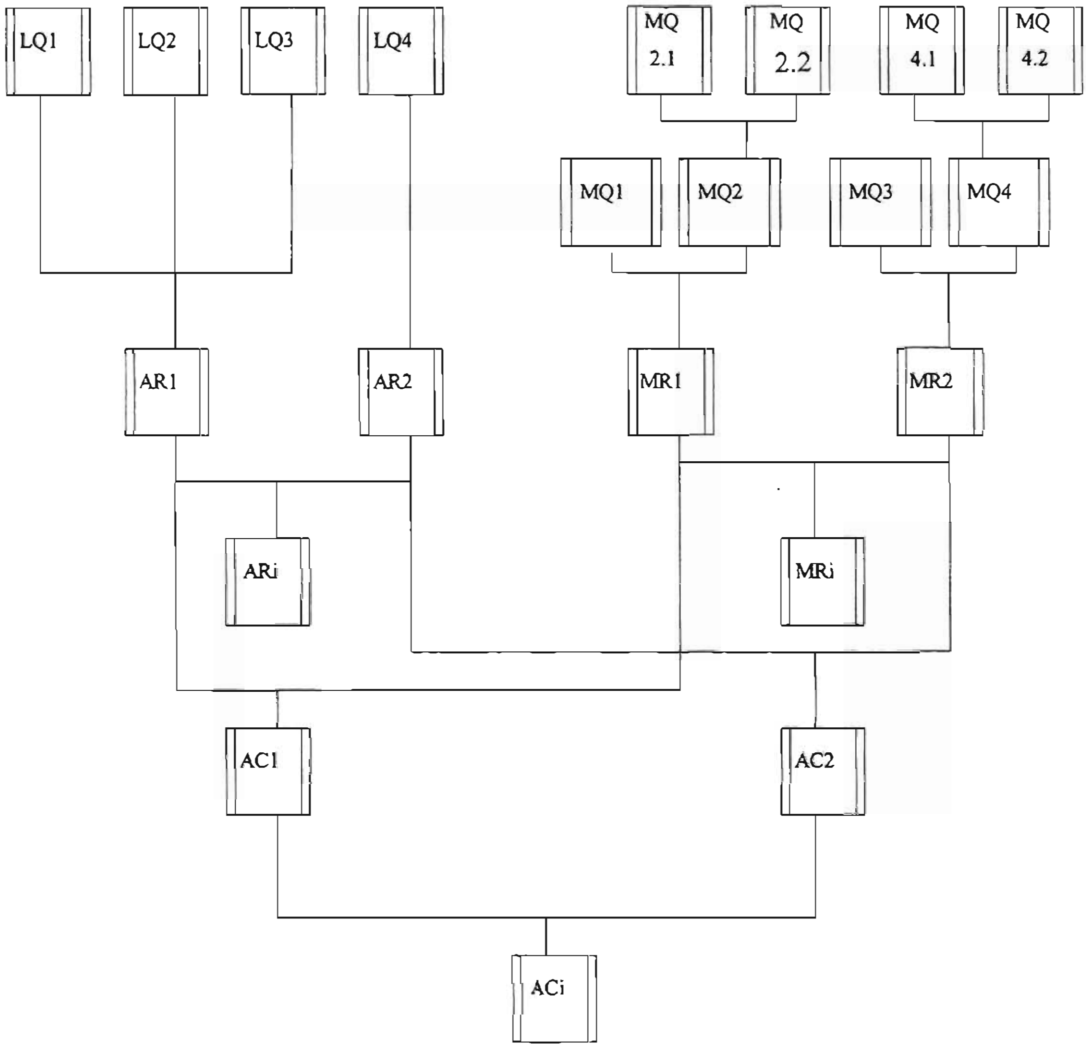

Figure 7.2. General scheme of the relations between land qualities (LQs), management qualities (MQs), and attainable (ARs), management (MRs) and actual (ACs) erosion vulnerability classes.

LQ2 Soil erodibility represents the resistance of the soil to both detachment and transport. Although soil resistance to erosion depends in part on topographic position, slope steepness and the amount of disturbance created by man, for example during tillage, the properties of the soil profile are the most important determinants. Erodibility varies with soil texture, aggregate stability, shear strength, infiltration capacity and organic and chemical content. LQ2 is formed by the following five LCs: Particle size distribution, Superficial stoniness, Organic matter, Surface drainage and Sodium saturation (Table 7.1).

LQ3 Rainfall erosivity is partly through the detaching power of raindrops striking the soil surface and partly through the contribution of rain to run-off. The most commonly used rainfall erosivity index is the ratio $2p/P$ (Fournier-Index) where p is the mean monthly precipitation and P is the mean annual precipitation. It is strictly an index of the concentration of precipitation in a single month and thereby gives a crude measure of the intensity of the rainfall and, in so far as a high value denotes a strongly seasonal climatic regime with a dry season during which the plant cover decays, of erosion protection by vegetation. The occurrence of a shower of rain after a dry period makes land especially vulnerable to soil erosion. This is why we changed the Fournier index to the "Derived Fournier/Humidity" index. This continuous LC is inferred from the monthly climate variables:

- Mean precipitation;
- Maximum precipitation;
- Mean temperature.

with the following formula:

$$K = \Sigma\, p^2max / \Sigma\, Pmax / HI \quad (7.1)$$

where, K = Derived Fournier/ Humidity index; pmax = Highest monthly precipitation during 30 years (mm); Pmax = Cumulative highest monthly precipitation of 30 year period for the 12 months of the year, i.e. the wettest year; HI = Humidity index. This continuous LC is inferred from the monthly climate variables: Mean precipitation, Mean temperature and Latitude with the following formulas:

$$HI = Pa / PETa \quad (7.2)$$

where, Pa = Annual amount of Precipitation (mm); PETa = Annual amount of Potential Evapotranspiration (mm). The calculation of monthly potential evapotranspiration (ET0) is according to the methods in Chapter 2. Note that H1 can take a maximum value of 1, even if it calculates to a value >1. LQ3 is only related to the LC derived Fournier/Humidity index. Each LQ separates four severity levels and all the LCs are relatively easy available.

b) Wind erosion
The process of wind erosion is the entrainment of soil particles by wind which applies a sufficiently large fluid force to the grains, and bombards static grains with grains already in motion (Morgan, 1979). The assessment of the **attainable wind erosion** vulnerability (AR2) is only related to LQ4 Wind erodibility. It is derived from easily available LCs such as Humidity index, Particle size distribution, Organic matter content and Depth of the ground water level, and is classified into ten severity levels.

The assessment of the **Total attainable soil erosion** vulnerability (ARi), which is the combination of water and wind (AR1 and AR2), is classified into total indices (Table 7.2).

7.2.2 Categories of classification
Ten vulnerability classes of each type of Attainable risk (AR) are defined:

Class V1: Nil. Field unit is not vulnerable to water or wind erosion and the risks from these processes can be considered as nil and the land unit will be uneroded. For fields with this attainable class; the management erosivity is not considered to be a controlling factor and almost any farming system can be implemented.

Class V2: Very Low. Field unit is little vulnerable to wind or soil erosion. Soil erosion will occur rarely and only during extreme climate events. For fields with this attainability class; the influence of the management systems on soil erosion is low.

Class V3: Low. The field unit is slightly vulnerable to water or wind erosion. Soil erosion will occur rarely. The soil could have a few rills or places with thin A horizons that give evidence of accelerated erosion, but not to an extent to greatly affect the thickness and character of the A horizon. The wind will only remove a very small amount of soil. No differences in use capabilities and management requirements to the uneroded soils. For fields with this attainability class; the effect of management system change on the (vulnerability) risk classes could be important.

Class V4: Moderately Low. The field unit is slightly to moderately vulnerable to water or wind erosion. Only a few indicators of water erosion (especially inter-rill erosion) will be visible in the field. The soil of the areas with this class can be eroded to the extent that ordinary implements reach through the remaining A horizon. Wind will remove a small amount of the soil. Small differences in use capabilities and management requirements from the uneroded soils. For fields with this attainable class; the effect of management system change on the (vulnerability) risk classes could be important.

Class V5: Slight. The field unit is moderately vulnerable to water or wind erosion. The soil will erode to the extent that ordinary tillage implements reach through the remaining A horizon, or well below the depth of the original ploughed layer in soils with thin A horizons. Generally, the plough layer will consist of a mixture of the original A horizons and underlying horizons. Mapped land units will have patches in which the plough layer consists wholly of the original A horizon and others in which it consists wholly of underlying horizons. A few shallow gullies will be present in the field. Wind will remove the same amount of the A horizon that ordinary tillage will bring up. For fields with this attainable class; the effect of management system change on the(vulnerability) risk classes could be important.

Class V6: Slightly High. The field unit is moderately vulnerable to water or wind erosion. The soil will erode to the extent that a large part of the original surface soil, or A horizon, will be removed. Water erosion processes will be active during each year. Shallow gullies will be present in the field. Wind will remove from the soil a large amount of the A horizon that ordinary tillage will bring up, and will partly mix the B horizon or other lower lying horizons with surface soil in the plough layer. Rarely will this condition be uniform throughout a mappable land unit. For fields with this attainability class; the effect of management system change on the (vulnerability) risk classes could be important.

Class V7: Moderately High. Field unit is moderately to highly vulnerable to water or wind erosion. The soil will erode to the extent that practically all of the original surface soil, or A horizon , will remove. The plough layer will consist essentially of materials from the B or other underlying horizons. Patches in which the plough the plough layer is a mixture of the original A horizon and the B horizon or other underlying horizons will be included within the mapped field units. Shallow gullies, or a few deep ones, will be common on some soil types. Wind will remove all of the A horizon and a small amount of the B or other lower lying horizon. The plough layer will consist of original horizons below the A horizon. For fields with this attainability class; the more erosive farming system management has adverse effects on the environment.

Class V8: High. The field unit is highly vulnerable to water or wind erosion. The soil will erode to the extent that all of the original surface soil, or A horizon will be removed. The plough layer will consist essentially of materials from the B or other underlying horizons. Patches in which the plough layer is a mixture of the original A horizon and the B horizon or other underlying horizons will occur within the mapped field units. Shallow and moderately deep gullies will be present in the field unit. Where land will be afforested or drained there will be often a "slug" of erosion before channels are stabilised by vegetation, but the rates of erosion will continue to be greater than those prevailing before. Wind will remove all of the A horizon and a part of the B or other lower horizon. The plough layer will consist mainly of the original horizons below the A(or below the original ploughed layer in the soils with thin A horizons), although some patches will have much of the original A horizon in the field unit. Sometimes occasional blow-out areas of the field unit will be included. For fields with this attainability class; the more erosive farming management systems have adverse effects on the environment.

Class V9: Very High. The field unit is very vulnerable to water or wind erosion. The field will erode until it will have an intricate pattern of moderately deep gullies. Soil profiles will be destroyed except in small areas between gullies. Such fields are not useful for crops in this condition. Reclamation for crop production or for improved pasture is difficult, but will be practical if other characteristics of the soil are favourable and erosion is controlled. The wind will remove a big part of the soil profile. The plough layer consists of the original horizons below the A-horizon. An occasional blow-out part of the field unit will be included.

Class V10: Extremely High. The field unit is extremely vulnerable to water or wind erosion. The fields will erode until they have an intricate pattern of moderately deep or deep gullies. Soil profiles will be destroyed except in small areas between gullies. Such fields are not useful for crops in this condition. Reclamation for crop production or for improved pasture is very difficult, but will be practical if the other characteristics of the soil are favourable and erosion will be controlled by soil conservation techniques, for example by construction of terraces. The assessment of the Attainable vulnerability (ARi) is classified into ten total indices. Besides classes, subclasses are also given as evaluation outputs. The meaning of the subclasses is to show the user which are the vulnerability limitations of the evaluated field unit and to support an understanding of the evaluated classification.

7.3 Soil and water contamination vulnerability expert model

The agrochemical contamination model is an expert qualitative land evaluation system for assessing attainable management and actual vulnerability of a field unit to diffuse (agro)chemical ground and/or surface water contamination within Europe. Types of field vulnerability contamination included in the model are: phosphate (+ arsenic); nitrogen; heavy metals; pesticides (hydrophilic + soluble organics, and hydrophobes), and soil acidification.

Within the framework of this model the influence of field management factors to the vulnerability of a particular soil is incorporated. This part of the model is not included in the EuroACCESS I model, because it is based at a local level and it needs detailed data.

Table 7.1 Pathways of the decision tree constructed for LQ2 Soil erodibility to water erosion (k) to develop the criteria for classification for AR1 attainable water erosion vulnerability. This decision tree is divided into classes of each LC. The path of the decision tree is followed until a severity level of LQ2 is encountered.

Evaluation		Classes		
Step	Characteristics (LC)	1	2	3
AA	Drainage	>BA	>BB	>BC
BA	Particle size distribution	>CA	>CB	>CC
BB	Particle size distribution	>CB	>CD	>CE
BC	Particle size distribution	>CE	>CF	4
CA	Organic matter	1	1	>DA
CB	Organic matter	>DA	>DB	>DC
CC	Organic matter	2	>EB	3
CD	Organic matter	>DC	>DD	>DE
CE	Organic matter	3.	>EC	4
CF	Organic matter	>DF	4	4
DA	Superficial stoniness	1	>EA	
DB	Superficial stoniness	>EA	2	
DC	Superficial stoniness	2.	>EB	
DD	Superficial stoniness	>EB	3	
DE	Superficial stoniness	3	>EC	
DF	Superficial stoniness	>EC	4	
EA	Sodium saturation	1	2	
EB	Sodium saturation	2	3	
EC	Sodium saturation	3	4	

Note: Under each class, the symbol > followed by a letter combination (BA to CD) is used to direct the user to the next step of the decision tree.

Table 7.2 Combination of vulnerability class types according to attainable, management and actual vulnerability to water, wind and total erosion.

Land degradation factor	Vulnerability evaluation		
	Attainable risk	Management risk	Actual risk
Water erosion, class	AR1	MR1	AC1
Wind erosion, class	AR2	MR2	AC2
Total, index	ARi	MRi	ACi

7.3.1 The assessment approach

The construction of this model is almost the same as the erosion model. The attainable vulnerability types (AR) are derived from ten Land Qualities (LQ) and twelve Land Characteristics (LC). All the twelve Land Characteristics used are reasonably easily available parameters: Landform, Slope, Drainage, Particle size distribution, Organic matter content, pH ($_{H2O}$), Cation exchange capacity, Parent rock, Humidity index, Annual mean temperature, Groundwater table depth, and Annual total rainfall. The division within the LCs is based partly on the classification used in the FAO/ISRIC/CSIC (1995) Soil database (SDBm). By combination of these Land Characteristics (LC) the following Land Qualities (LQ) are obtained (Table 7.3): Surface run-off (Relief, Soil erodibility and Rainfall erosivity), Leaching degree, Acid rainfall contamination, Pesticide sorption, Biodegradation, Denitrification, Acid buffering capacity, Phosphate fixation and Ammonia volatilisation.

Table 7.3 Combination of vulnerability class types according to attainable management and actual soil and groundwater contamination.

Agrochemical contamination compounds	Vulnerability Type		
	Attainable	Management	Actual
Phosphate, class	AR1	MR1	AC1
Nitrogen, class	AR2	MR2	AC2
Heavy Metals, class	AR3	MR3	AC3
Pesticides, class	AR4	MR4	AC4
- Hydrophilic, class	AR4.1	"	AC4.1
- Hydrophobic, class	AR4.2	"	AC4.2
Soil Acidification, class	AR5	MR5	AC5
Total, index	ARi	MRi	ACi

Attainable vulnerability types (AR) are derived from the Land Qualities (LQ) used. The following ARs are used:

AR1 Phosphate/Arsenic,
AR2 Nitrogen,
AR3 Heavy metals,
AR4 Pesticides (AR4.1 Hydrophilic and soluble organics, AR4.2 hydrophobics)
AR5 Soil Acidification.

Combination of all ARs gives the total index of the attainable (agro)chemical contamination vulnerability (Ari).

AR1 Attainable Phosphate / Arsenic contamination is formed from the following Land Qualities: LQ9 Phosphate fixation, LQ1 Surface Run-off and LQ2 Leaching Degree. AR1 is dependent on the following Land Characteristics: Landform, Slope Gradient, Drainage, Particle Size Distribution, Organic Matter, Humidity Index, Amount of Rainfall (annual), Groundwater Table Depth and pH(H_2O).

AR2 Attainable Nitrogen contamination is formed by the following Land Qualities: LQ2 Leaching Degree, LQ8 Cation Adsorption Capacity, LQ6 Denitrification and LQ1 Surface Run-off. AR2 is dependent on the following Land Characteristics: Humidity Index, Groundwater Table Depth, Drainage, Particle Size Distribution, pH($_{H2O}$), Cation Exchange Capacity, Organic Matter, Accumulated monthly Temperature, Physiographical Position, Slope Gradient and Amount of Rainfall (annual).

AR3 Attainable Heavy Metals contamination is formed by the following Land Qualities: LQ8 Cation Adsorption Capacity, LQ1 Surface Run-off and LQ2 Leaching Degree. AR3 is dependent on the following Land Characteristics: pH($_{H2O}$), Particle Size Distribution, Cation Exchange Capacity, Organic Matter, Physiographical position, Slope Gradient, Drainage, Humidity Index, Amount of Rainfall (Annual) and Groundwater Table Depth.

AR4 Attainable Pesticides (Hydrophilic/ Hydrophobic) and Soluble organic contamination is formed by the following Land Qualities: LQ2 Leaching Degree, LQ4 Pesticides Sorption, LQ1 Surface Run-off and LQ5 Biodegradation. AR4 is dependent on the following Land Characteristics: Humidity Index, Groundwater Table Depth, Drainage, Particle Size Distribution, Organic Matter, pH($_{H2O}$), Cation Exchange Capacity, Physiographical position, Slope Gradient, Amount of Rainfall (annual) and Accumulated Monthly Temperature.

AR5 Attainable Soil Acidification is formed by the following Land Qualities: LQ7 Acid Buffer Capacity, LQ3 Rainfall Contamination, LQ2 Leaching Degree, LQ12 Ammonia Volatilisation and LQ6 Denitrification. AR5 is dependent on the following Land Characteristics: Parent Rock Type, pH($_{H2O}$), Cation Exchange Capacity, Organic Matter, Rainfall (annual average), Humidity Index, Groundwater Table Depth, Drainage, Particle Size Distribution, Annual Temperature.

7.3.2 Categories of classification

The agrochemical contamination vulnerability classes (4) established by the contamination model for the attainable vulnerability (AR1 to AR5) are defined as:

Class V1: Very Low. Scarcely vulnerable to agrochemical contamination (soil acidification) by agricultural activities and the biophysical risks to soil, surface and groundwater diffuse pollution are very low. The corresponding fields have a very large storage capacity for agrochemical compounds and/or the amount of leaching, run-off of the contaminants is very low.

Class V2: Low. A reasonably low vulnerability to agrochemical compounds which contaminate the soil, surface and groundwater diffusely, and to soil acidification. The agropollutant storage capacity of the corresponding fields is high, and/or the amounts of leaching and run-off are low.

Class V3: High. A reasonably high vulnerability to agrochemical compounds which contaminate the soil, surface and groundwater diffusely, and to soil acidification. The agropollutant storage capacity of the corresponding fields is low and/or the amount of leaching, run-off ranges from moderate to high.

Class V4: Very High. Very vulnerable to agrochemical contamination or soil acidification by agricultural activities, and the risks to soil, surface and groundwater diffuse pollution are severe. The corresponding fields have a very small storage for agrochemical compounds, and therefore the leaching could be very high. Also fields which are strongly vulnerable to run-off could damage the quality of surface water.

Besides classes, subclasses are also presented as evaluation outputs. The meaning of the subclasses is to show the user which are the vulnerability limitations of the evaluated field unit and to support to understand the evaluated classification.

7.4 Incorporating land management factors

As demonstrated in the development of the vulnerability models, an important goal of this group is the incorporation of land management factors into biophysical land evaluation approaches. This concept was developed in response to the growing need for integrating agronomic information into land evaluation (IBSRM, 1991; Mayr *et al.*, 1993; Robert *et al.*, 1993). An approach to this is illustrated in Figure 7.4. Phase 1 deals with the biophysical part and phase 2 with the management part. Another difference between the two phases is the scale: European (phase 1) versus regional *e.g.* Andalucia (phase 2). In phase 2 the Management Knowledge Base is essential to run this part of the model. This database contains management information, which is described exclusively in technical terms. Three land management levels are identified for Andalucia: Intensive, Moderate and Extensive.

At the moment this knowledge base contains 25 Field Utilisation Types (FUT). A FUT is an extension of the Land Utilisation Type (LUT) with special attention to agronomic or management characteristics. Each FUT is divided into two Management Categories (MQ): 1) crop properties and 2) cultivation practices. A MQ is a complex attribute of land management. Each MQ is formed by Management Characteristics (MCs), an attribute of management that can be estimated and used to describe MQs. Table 7.4 shows an example of one particular FUT (FUT#16 Rice/Intensive). Each FUT also shows its expected behaviour corresponding with a representative benchmark area. Table 7.5 shows a summary of management characteristics and classes from the current knowledge base for selected field management systems of Andalucia.

The central concept of "attainable suitability or vulnerability" is the suitability or vulnerability within the biophysical limitations of the land unit. However, in reality "attainable" is an ideal or potential, and "actual" is the norm. The latter depends on land management, which often affects the constraints imposed through the properties of the land unit. The combination of the land management (Land use type, LUT) and land unit (LU) forms the Land use system (LUS). The Actual vulnerability considers simultaneously the biophysical and land management risk factors of a particular field unit. The model separates the actual vulnerability classes for each vulnerability type (AC). The spatial unit of evaluation is the field unit.

7.4.1. Soil erosion management approach

The classification of the management water erosion vulnerability (MR1) is based on two MQs: MQ1 Crop properties and MQ2 Cultivation practices. MQ2 is subdivided into MQ2.1 Cultivation practices/Soil and MQ2.2 Cultivation practices/Plant. Each MQ has four severity levels and they are formed by a combination of MCs.

MQ1 Crop properties is formed by a combination of the following seven MCs: Crop type, Growing season length, Leaf duration, Sowing date, Specific leaf area (SLAmax), Crop height and Rooting depth.

MQ2.1 Cultivation practices/Soil is formed by a combination of four MCs: Tillage practices, Depth of tillage, Soil conservation techniques and Artificial drainage.

MQ2.2 Cultivation practices/Plant is formed by a combination of three MCs: Row spacing, Rotation and Residues treatment.

Table 7.2 shows the framework of the expert system, incorporating the attainable, management and actual submodels. Finally, the model evaluates the actual water erosion vulnerability by combination of the attainable and management vulnerability classes. The management wind erosion vulnerability assessment (MR2) is formed by MQ3 Crop properties and MQ4 Cultivation practices.

MQ3 involves the following MCs: Crop type, Growing season length, Situation of the leaves, Structure and Height of the crop.

MQ4 is formed by combining the following MCs: Types of tillage practices, Methods of soil tillage, Soil conservation techniques, Crop rotation and Residues treatment. Each MQ separates four severity levels.

Table 7.6 shows the "Input Variable List" of the soil erosion model, including Land and Management Characteristics.

a) Categories of classification

Four management vulnerability classes are defined for each type of Soil Erosion Management Vulnerability (MR1 and MR2).

Class V1: Very Low. The human influence on the field unit is very small in terms of vulnerability to water or wind erosion. In general, this class represents good soil conservation methods and the actual vulnerability of a field unit will be only dependent on the attainable risk. This class represents the best field management methods for a particular field unit to get a possibly sustainable land use system (economical issues are not involved).

Class V2: Low. The influence of the field management is small in terms of water or wind erosion vulnerability. In the sense of sustainable land use; when the attainable (bio-physical) risk is high then the risk of field management has to be Class 1. Very Low or Class 2. Moderately Low. Land uses with higher vulnerability are excluded.

Class V3: High. A field unit with this risk class is in danger of becoming less suitable in an agricultural sense and its field methods are vulnerable to water or wind erosion. The field use with this management risk is considered not to be sustainable.

Class V4: Very High. Field units with this management class are in real danger of becoming unsuitable, because their management methods accelerate the processes of water or wind erosion to a high degree. To sustain the field it is necessary to avoid this management class.

The assessment of the Management soil erosion vulnerability (MRi) is classed into five total indices. Ten actual vulnerability classes of each type of Actual vulnerability (AC1 and AC2) are defined. These definitions are exactly the same as the definitions of the Attainable vulnerability (AR; see Section 7.2.2). The assessment of the Actual soil erosion vulnerability (ACi) is classed into ten total indices.

7.4.2 Soil and water contamination management approach

Within the management vulnerability model the following Management Characteristics (MC) are involved: Land use type; Crop rotation; Use of fertilisers: P, N, CaCO3, NH4, pig, industrial/urban waste and/or sewage water, nitrogenous organic waste and injection of nitrogenous; Time of fertilisation; Use of pesticides: amount, persistence, toxicity, and application methods; Artificial drainage, and ground water level rise; Soil management; Straw incorporation; Conservation techniques, Land use on slopes, Tillage practices, intensive stock farming. The following Management Qualities (MQ) are used: management susceptibility to Phosphate/Arsenic (MQ1), Nitrogen (MQ2), Heavy metals (MQ3), Pesticides (MQ4), Soil acidification (MQ5), Soil erosion (MQ6) and Ammonia volatilisation (MQ7).

The following Management vulnerability types (MR), which are derived from the Management Qualities used, are involved: contamination to Phosphate/Arsenic (MR1), Nitrogen (MR2), Heavy metals (MR3), Pesticides (MR4) and Soil Acidification (MR5). Combination of all MRs gives the total index of the management (agro)chemical contamination vulnerability (Mri).

Finally, you get - by combination of the attainable and management parts - the Actual vulnerability model. Within this part the following Actual vulnerability types (AC) could be evaluated: contamination to Phosphate/Arsenic (AC1), Nitrogen (AC2), Heavy Metals (AC3), Pesticides (AC4; hydrophilic AC4.1, and hydrophobic AC4.2) and Soil Acidification (AC5). Combination of ARi and MRi gives the total index of the actual (agro)chemical contamination vulnerability (Aci). Table 7.7 shows the "Input Variable List" of the soil contamination model, including Land and Management Characteristics.

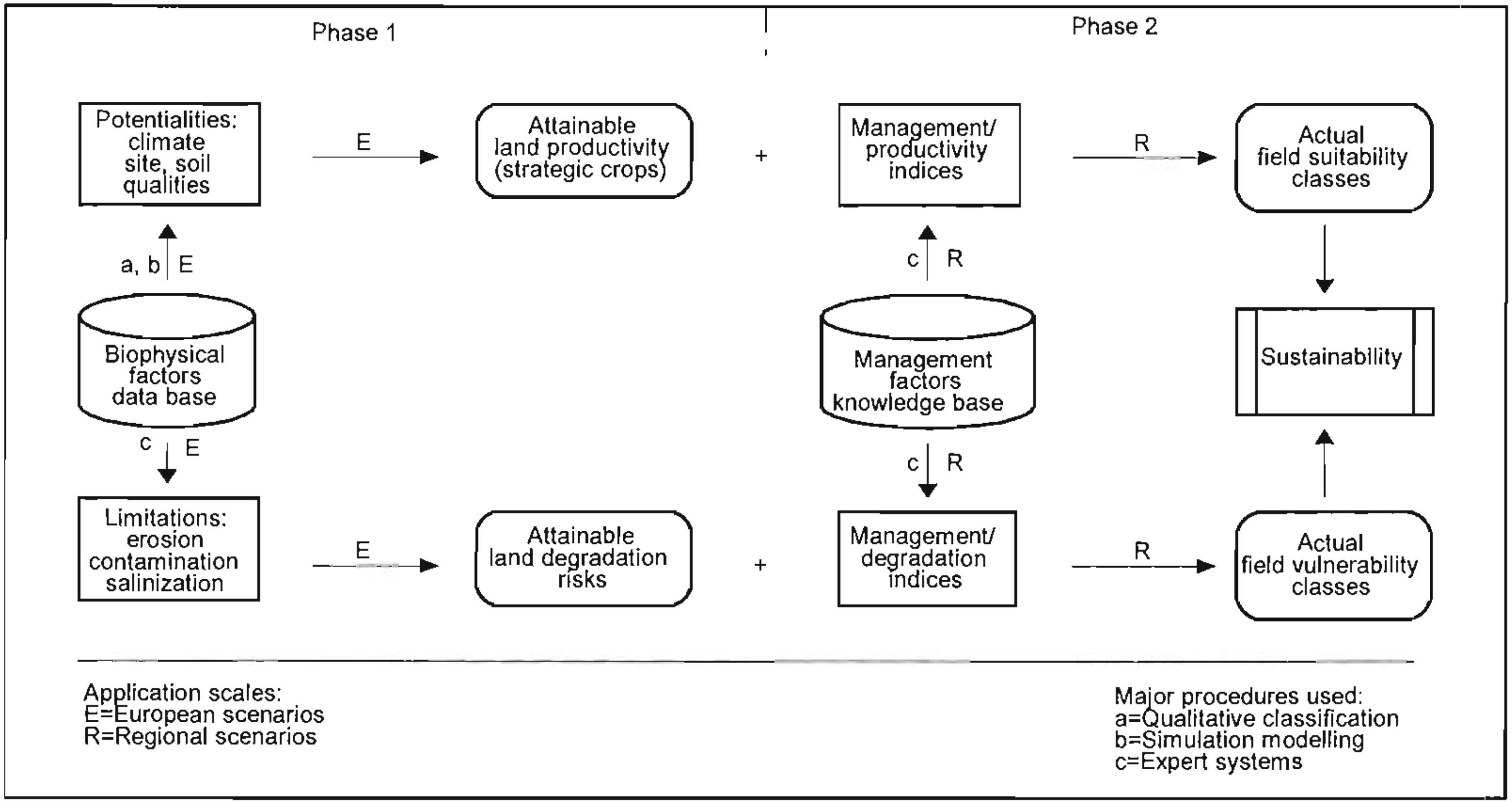

Figure 7.3 General scheme for integrating the land management factors in a traditional land evaluation framework

Table 7.4 An example of 'soft' information, FUT#16: Rice/Intensive, inventoried for the main current FUT's in Andalucia region

Variable:	**number/amount; type; timing**

Crop properties

Main varieties of *Oryza indica* L. : Thaibonnet
Plant height, max.: 0.4 - 0.7 m
Rooting depth, max.: 0.6 - 1.0 m
Leaf area, SLA (LAI)max.: 27 (8-9)
Growing season length: 110 - 130 days
Duration development stages: 10, 30, 20, 40, 20
Crop coefficients, Kc/stage: 1.12, 1.12, 1.20, 1.00, 1.00
Harvest index: 0.40 - 0.50

Cultivation practices

Primary tillage: 1-2, mouldboard ploughing, Nov-Feb; 2, disk cultivator; Mar-Apr
Secondary tillage: nil
Sowing: 150-180 kg/ha; by plane; May
Plant density: 2.5 - 3.5 million plants/ha
Fertilisers: 30.000-50.000 kg/ha compost, every 4-5 years; 300 kg/ha, urea 46%; Apr
Fertiliser requirements: 130-150 N, 30 P, 0 K kg/ha
Herbicides: 1-2; post-emergence; May
Insecticides: 2-4; Jun-Jul
Harvesting: combine with caterpillar; Sep
Residues: straw ploughed-in; Sep-Oct
Irrigation: 10-15 thousand m3/ha; permanent flooding method; I/May-III/Aug
Artificial drainage: nil
Conservation: nil
Rotation: nil

Expected behaviour*

Production, yield/quality: 6.0-7.5 t/ha, 14 % moisture
Environmental impact, erosion/contamination risk: low/high

(*) Expected behaviour of this FUT corresponds to the representative area SE-05: Marismas, Sevilla

Table 7.5 Summary of MC's and their classes from the management knowledge inventory referred to the main current FUT's in Andalucia region.

Management Characteristics	Classes 1	2	3	4
		Crop properties		
Plant type	nil	set aside	annual	perennial
Plant age	seedling	juvenile	full size	old
Plant height, cm	<100	100-175	175-250	>250
Rooting depth, cm	<50	50-100	100-150	>150
Leaf size, cm2	<2	2-10	10-50	>50
L A I, max.	<5	5-8	8-10	>10
G S L, day	<150	150-200	200-225	>225
Kc, mid-season	<0.9	0.9-1.1	1.1-1.2	>1.2
Harvest index	<0.15	0.15-0.30	0.30-0.60	>0.60
		Cultivation practices		
Primary tillage:				
Ploughing, times	nil	1	2-5	
Cultivation, times	nil	1	2-5	>5
Plastic cover	no	yes		
Secondary tillage:				
Cultivation, times	nil	1	2-5	>5
Clearing, times	nil	1		
Rolling, times	nil	1	2-5	>5
Plant density, (plant(000's)/ha)	<5	5-50	50-1000	>1000
Row spacing, cm	<15	15-70	70-200	200-1000
Sowing/planting date	autumn	winter	spring	summer
Fertilisers, kg/ha:				
N	nil	50-100	100-250	>250
P	nil	20-30	30-60	>60
K	nil	30-50	50-75	>75
Herbicides, times	nil	1	2-4	
Insecticides, times	nil	1	2-5	
Irrigation:				
Times	nil	1	2-5	>5
System	nil	drip	sprinkler	furrow
Artificial drainage	no	yes		
Harvesting	manual	mechanical		
Harvesting date	autumn	winter	spring	summer
Crop residues	nil	burning	ploughed-in	
Conservation	nil	few	many	
Rotation	nil	winter-summer	annual-perennial	independent

Table 7.6 Input land and management characteristics of the erosion model.

Site-related land characteristics

LC Physiographical position, classes
LC Slope gradient, %
LC Groundwater table depth, m

Soil-related land characteristics

LC Drainage, classes
LC Particle size distribution, classes
LC Superficial stoniness, %
LC Organic matter, %
LC Sodium saturation, %

Climate-related land characteristics

LC Mean monthly precipitation, mm
LC Max. monthly precipitation, mm
LC Mean monthly temperature, °C
LC Latitude, °

Crop-related management characteristics

MC Plant type, classes
MC Leaf duration, classes
MC Growing season length, days
MC Situation of leaves, classes
MC Specific leaf area (SLAmax), $m^2\ kg^{-1}$
MC Plant height, m
MC Maximum rooting depth, m
MC Structure of crop, classes

Cultivation-related management characteristics

MC Sowing date, classes
MC Tillage practices type, classes
MC Depth of tillage, m
MC Methods of soil tillage, classes
MC Row spacing, m
MC Artificial drainage, classes
MC Soil conservation techniques (water), classes
MC Soil conservation techniques (wind), classes
MC Residues treatment, classes
MC Crop rotation, classes

The agrochemical contamination vulnerability classes (4) established by the contamination model for management vulnerability (MR1 to MR5) are defined as:

Class V1: Very Low - lowers the quality of the soil, surface and groundwater of the field unit.

Class V2: Low - harms the quality of the soil, surface and groundwater of the field unit on a small scale.

Class V3: High - damages the quality of the soil, surface and groundwater of the field unit on a high scale

Class V4: Very High - harms the soil, surface and groundwater quality of the field unit on an extremely high scale.

The total assessment of the Management agrochemical contamination vulnerability (MRi) is classified into indices 1 to 10. The definitions of the total indices could be derived from the above written descriptions of attainable and management vulnerability classes.
The assessment of the actual vulnerability (AC1 to AC5) is classified into five actual vulnerability classes:

Class V1: Very Low. Field units which correspond to this class are scarcely vulnerable to agrochemical contamination or soil acidification, because of its biophysical condition and its management system. The actual vulnerability to soil, surface and groundwater diffuse pollution is very low. This management system is not considered to be a controlling factor and almost any farming system could be implemented.

Class V2: Low. Field units which correspond to this class are slightly vulnerable to agrochemical contamination or soil acidification, because the combination of the management system with the biophysical conditions of the field unit does almost no harm to the soil, surface and groundwater quality.

Class V3: Moderate. Field units which correspond to this class are moderately vulnerable to agrochemical contamination or soil acidification. The combination of the management system and biophysical characteristics of the field unit harms the quality of soil, surface and groundwater.

Class V4: High. Field units which correspond to this class are highly vulnerable to agrochemical contamination or soil acidification, because the simultaneous impact of the management system and the biophysical characteristics damages the quality of the soil, surface and groundwater of the field unit on a high scale. More intensive farming systems have adverse effects on the environment.

Class V5: Very High. Field units which correspond to this class are extremely vulnerable to agrochemical contamination or soil acidification, because the intensity of the agricultural activities on the field unit and the high biophysical vulnerability of the field unit itself harm the soil, surface and groundwater quality on an extremely high scale.

The total assessment of the Actual agrochemical contamination (ACi) is classified into indices 1. to 10, which can be derived from the above written descriptions of the actual vulnerability classes.

Table 7.7 Input land and management characteristics of the contamination model.

Site-related land characteristics

LC Landforms, classes
LC Slope gradient, %
LC Parent rock type, classes
LC Groundwater table depth, m

Soil-related land characteristics

LC Drainage, classes
LC Particle size distribution, classes
LC Organic matter, %
LC pH(H2O)
LC Cation exchange capacity, meq/100g

Climate-related characteristics

LC Mean monthly precipitation, mm
LC Mean monthly temperature, °C
LC Latitude, °

Crop-related management characteristics

MC Land use type, classes
MC Crop rotation, classes
MC Intensive stock farming, classes
MC Land use on slopes, classes

Fertiliser-related management characteristics

MC Amount of P-fertiliser, classes
MC Amount of N-fertiliser, classes
MC Use of liming materials as fertilisers, classes
MC Use of ammonium-fertiliser, classes
MC Use of pig manure and/or P-fertiliser, classes
MC Inundation of land by industrial /urban waste and/or sewage water, classes
MC Use of nitrogenous organic waste, classes
MC Injection of nitrogenous fertilisers, classes
MC Time of fertilisation, classes

Pesticides-related management characteristics

MC Use of pesticides, classes
MC Persistence of pesticides, classes
MC Toxicity (LD-50) of pesticides, classes
MC Application methods, classes

Other cultivation-related management characteristics

MC Artificial drainage and/or groundwater level rise, classes
MC Soil management (ploughing), classes
MC Straw incorporation, classes
MC Soil conservation techniques, classes
MC Tillage practices, classes

7.4.3 Sustainability assessment approach

The term "sustainability" is generally used to indicate the limits placed on the use of ecosystems by man. Obviously, land evaluation touches on different aspects of sustainability as it focuses on one important natural resource: the land

(Bouma *et al.,* 1993a, b). New land evaluation procedures must estimate land use and management not only in terms of production efficiency but also in terms of its impact on the environment (Figure 7.3). A sustainable land use system would be one in which the potentials corresponding to the suitability class are equal to or greater than the limitations corresponding to the vulnerability class. The integration of both criteria (suitability and vulnerability) can define the sustainability, as a sustainable or an optimum land use must include maximum field suitability and minimum field vulnerability. In this sense it describes an optimal approach to the assessment of sustainability; and tries to measure field suitability and vulnerability so that agricultural production works with and not against it.

7.5 Automated data processing

The core of the evaluation models (decision trees) were initially developed within the ALES framework (Rossiter, 1990), and then translated into Microsoft™ C++. The programming is compatible with Microsoft™ FORTRAN (Version 5.0) which is the general software for EuroACCESS. However, an important part of the model is a Nantucket CLIPPER™ (Version 5.1) program with menus and explanation screens to aid generation (preparation and editing) of input data for the models; and another program to display (in tabular and/or graphical mode) results of the evaluation. Thus it is easy to modify parameters, create hypothetical scenarios, run the evaluation and observe their effects. Input data can be entered from the computer keyboard for groups of land or field units to be evaluated. In general these data are parameters from soil survey and other natural resource inventory information Also, an interface with the SDB and CDB databases (below) was developed to import the input parameters. The inclusion of a soil layer (control section), the soil characteristics to be included, and the means by which the characteristics per layer are determined (*e.g.* weighted averages, dominant values) to generate the data files to be used in the evaluation models (Crompvoets *et al.* 1993).

7.5.1 Databases

A climate database (CDB) was constructed to store all the meteorological data (monthly and daily). Daily parameters in this database were as follows:

- temperature max., mean, min.,
- humidity at 1, 7, 13, 18 hours,
- evaporation,
- sunshine hours,
- insolation, wind speed and direction at 7, 12, 18 hours and max. wind speed and its direction.

Monthly parameters were: precipitation; temperature: maximum, mean and minimum. The CDB will perform the following calculations:

- missing values (correlations between weather stations depending on altitude and distance),
- monthly to daily data,
- potential evapotranspiration (Thornthwaite or Penman),
- erosivity index,
- leaching index,
- growing season length,
- statistics (mean, range and standard deviation).

Further, it is possible to choose Spanish or English language options. All soil data are stored in the FAO/ISRIC/CSIC Soil database (1995), which was created in part by the Sevilla group. This database is a user-friendly tool to facilitate the organisation, storage and retrieval of basic soil data on a micro-computer. The following types of soil information are stored in this database:

site: profile, analytical, soluble salt and physical data.

The linkage between SDBm and the vulnerability models is made by using the "Soil layer generator" option of the SDBm database.

7.5.2 Hypothetical evaluations

The user has the option to generate hypothetical predictions by changing the climate or/and management related variables. So, it will be possible to predict for example the impact of climate changes on the field vulnerability to soil erosion, or to predict the impact of a Land Utilisation System of a field unit to water erosion.
Within the model it is possible to define any arbitrary set of climate perturbation(s) as the hypothetical climate change. Maximum and mean precipitation (%), and mean temperature (^{o}C) are the climate related factors which could be applied as the climate change increments (+ or -). The management change evaluation can be made by changing:

1. Field Utilisation Type. Selecting a particular FUT, which will be imposed to all the evaluation-units of an evaluating scenario.
2. Particular Management Characteristics. Selecting the classes of the MCs which will be imposed to all the evaluating-units of an evaluating-scenario.